Space-Based Gravitational Wave Data Analysis Development

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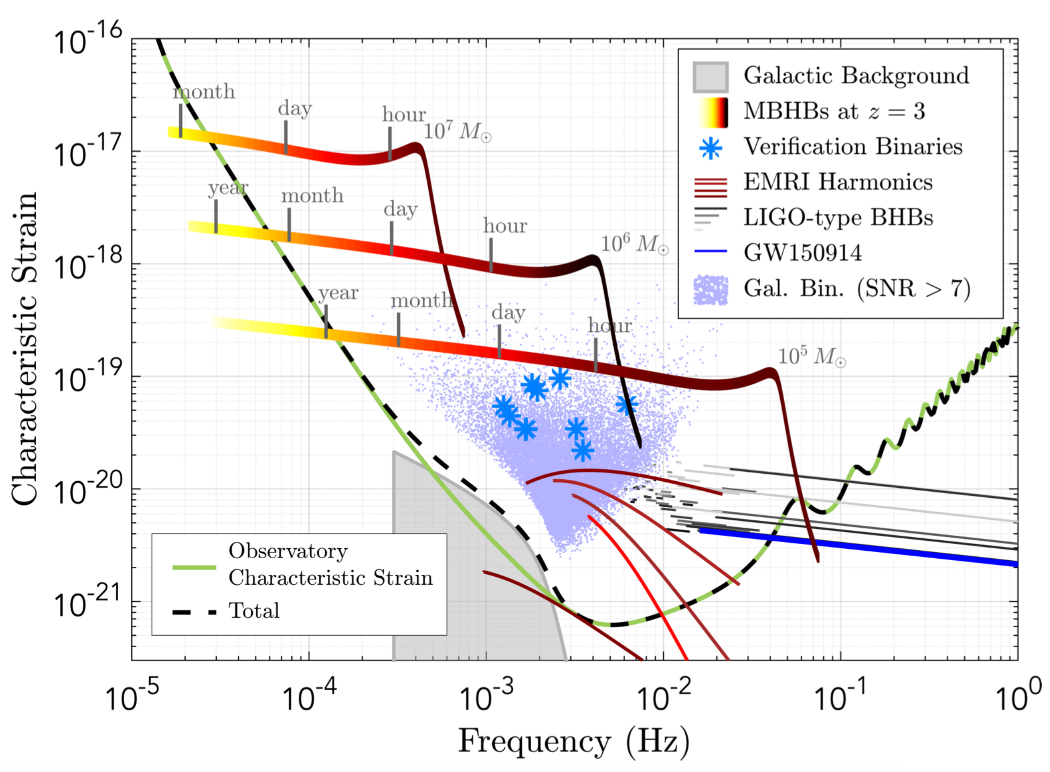
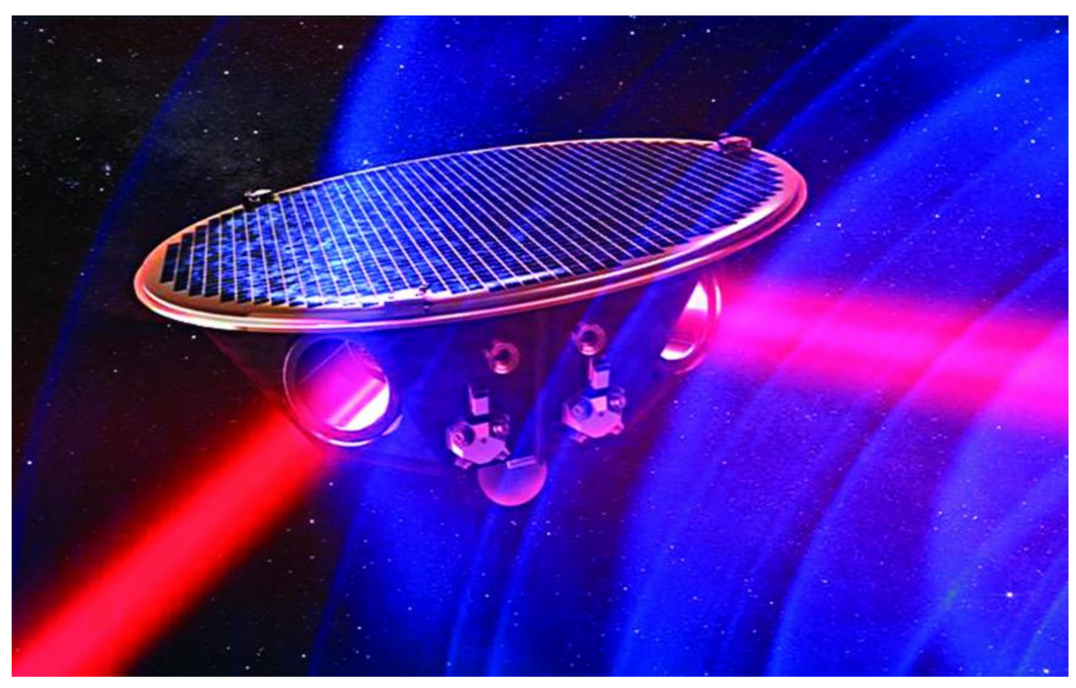
Space-Based Gravitational Waves and LISA



- LISA (Laser Interferometer Space Antennae) is a near-future mission (2034) to measure gravitational waves (GW).
- Emitted from some of the most elusive and energetic events in the Universe.
- Accessible source frequency range 10^{-5} to 10^{-1} Hz (unlike ground-based instruments such as LIGO)
- Measurement test masses aboard three separate spacecraft in heliocentric orbit.
- Separated by a distance of L = 2.5 x 10^6 km.
- Each spacecraft with two optical links for digital interferometry.
- GW detected by change in test mass separation δL like LIGO. However many differences and challenges in the data analysis methods for spaced-based GW detectors are present and will be discussed here.



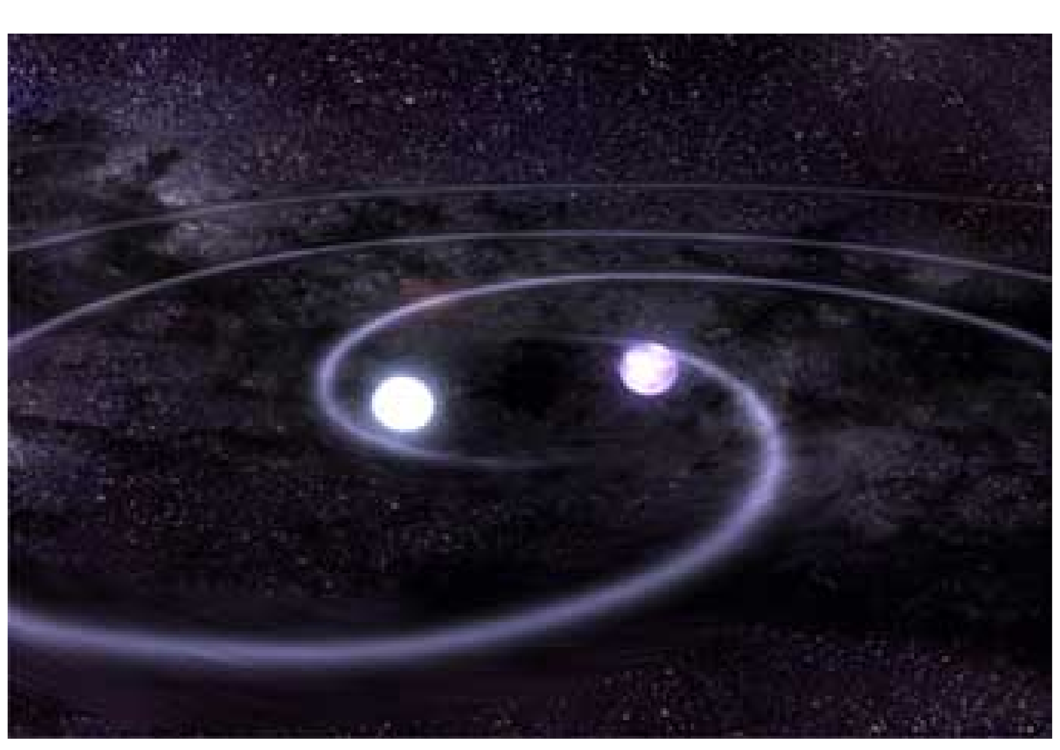
Galactic Binaries for Calibration

LISA is expected to detect around 2.5 x 10^4 WDB systems in the galaxy, around 10^2 of which will have EM observations from Gaia and the LSST [3]. Their gravitational waveforms are nearly continuous, and therefore considered verification binaries since their parameters can be compared to those obtained from EM analyses. This means they provide a calibration system independent of those implemented in mission design.

$$h(t) = A\sin[2\pi(f + \frac{\dot{f}t}{2})t + \varphi_D(t) + \varphi_0]$$

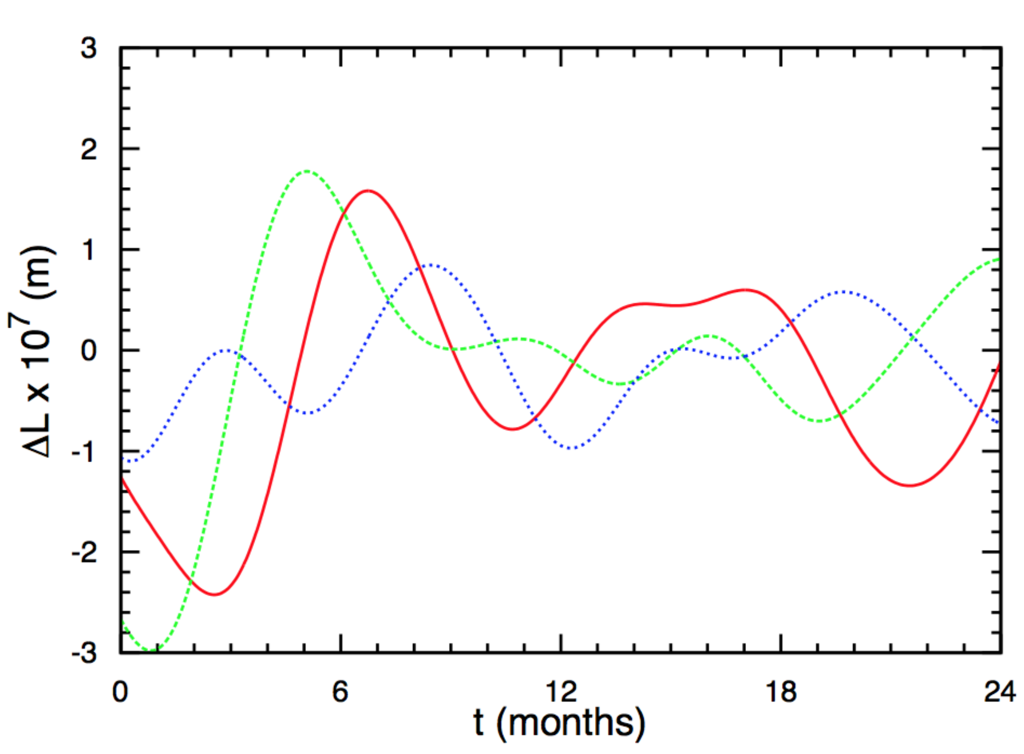
Allows for:

- Estimation of temporal gaps expected to be present in data by simple phase shift estimation in waveforms ($\frac{df}{dt}$ expected to be small, but further studies may examine this).
- Estimation of total error in phase ($\delta\varphi$) and amplitude (δA) as additional hyper-parameters in MCMC.



Time-Delay Ranging (TDIR) in MCMC

Unlike ground-based LIGO, the distances between test masses are not fixed, leading the variable arm-length of the interferometers to cause laser frequency noise (LFN) to be present in the data; amounting to 10^7 times greater strain ($\frac{\delta L}{L}$) than the expected strain due to gravitational waves ($\frac{\delta L}{L} \lesssim \frac{10^{-20}}{\sqrt{\mathrm{Hz}}}$). Time-delay interferometry (TDI) is the accepted method of suppressing LFN by delaying the phase measurements transmitted from individual spacecraft by a duration D corresponding to the relative separation, then combining delays to cancel the LFN which requires 100 ns timing accuracy.



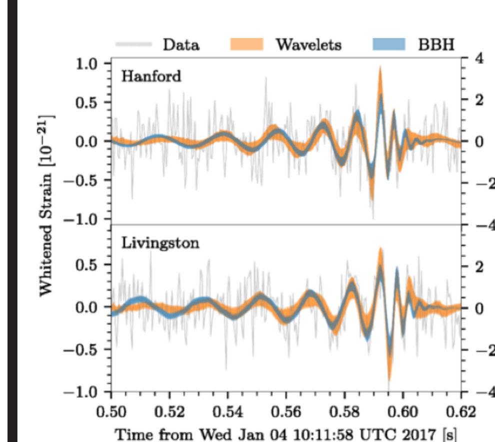
Rather than delaying the signals in pre-processing, **fractional-delay interpolation (FDI)** re-samples the signal with the non-integer delay D, given equally-spaced raw phase measurements. The delay will then be estimated as an additional parameter in the same MCMC used in GW signal analysis.

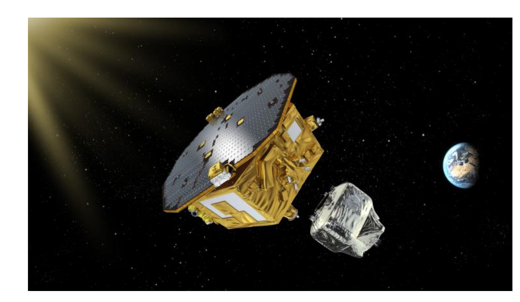
Bayesian Analysis for GW

A currently implemented analysis algorithm Bayeswave [4] used in ground-based GW inference will form the foundation for adaptation in space-based (SB) measurements.

$$p(h|s, M) = \frac{p(h|M)p(s|h,M)}{p(s|M)}$$

- Infers posterior distribution of waveform h given data and model, $p(h|s, M)$
- Model is either: GW signal, noise, or glitch.
- Multi-dimensional reverse-jump Monte Carlo Markov Chain (MCMC) in Bayeswave finds evidence and complexity (number of wavelets for reconstruction) for each model to determine confidence in astrophysical origin and estimates signal waveform parameters for source characterization.





This method has been consistent in all of the last three LIGO BBH detections. A similar algorithm for SB detection with LISA will be developed and tested on LISA Pathfinder data to determine how noise models may need modification due to different noise sources and properties.

Next Steps for FDI

FDI convolves the data with a sine cardinal finite impulse response (FIR) with a defined delay [2].

$$s(n - D) = s(n) * \mathrm{sinc}(n - D)$$

Since TDI requires 100 ns timing accuracy, the FIR approximation yielding the least interpolation error without loss of data will be found.

$$\varepsilon = \max(|H(f) - e^{\frac{-2i\pi fD}{f_s}}|_{1\mathrm{mHz} \le f \le 1\mathrm{Hz}})$$

Sinc filters currently being tested include Blackmann and Hammond windowed-sinc filters and the LaGrange filter. Of these, the Blackmann windowed-sinc filter w_b^3 is expected to be optimal in testing the relative difference in the delayed re-sampling of the data with original simulated data.

$$w_b = 0.42 + 0.5\cos(\frac{\pi n}{N-1}) + 0.08\cos(\frac{2\pi}{N-1})$$

Acknowledgements

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References

[1] D. Shaddock *et al.* *Postprocessed time-delay interferometry for LISA* Physical Review D, vol. 70, Issue 8, id. 081101

[2] T. Laakso *et al.* *Splitting the Unit Delay* IEEE Signal Processing Magazine

[3] V. Korol *et al.* *Prospects for detection of detached double white dwarf binaries with Gaia, LSST and LISA* MRNAS March 2017

[4] T. Littenberg N. Cornish *BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches* Classical and Quantum Gravity, Volume 32, Number 13